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The capture of electrons by positively charged traps in semiconductors

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The capture coefficient of hot electrons by positively charged centres is calculated, assuming that the capture takes place by the emission of optical phonons. It is shown that the capture coefficient increases with the increase of the external electric field. The increase in the capture coefficient is not sufficiently rapid to produce negative differential conductivity.

1. INTRODUCTION

Study of the variation with energy of the electron capture coefficient by neutral and negatively charged centres was first carried out by Zucker & Conwell (1961). A set of work in this area was done later by Pratt & Ridley (1965). Bonch-Bruevich (1961) and Wisbey & Ridley (1970). Until now not much attention was paid to the capture of electrons by positively charged centres. In the present work the capture coefficient of electrons by positively charged centres in n-type germanium at low temperature $T = 20°$K is studied. It is assumed that the capture of electrons by positively charged traps takes place by the emission of optical phonon

The probability of this process according to Lax (1960) can be written as

$$\sigma(\epsilon) = AP(\hbar\omega_0-\epsilon)\epsilon^{-1}\left(1-\frac{\epsilon}{\hbar\omega_0}\right)^{-5/2}\frac{\hbar\omega_0}{K_0T}\left[1-e^{-\frac{\hbar\omega_0}{K_0T}}\right]^{-1} \quad \ldots \quad (1)$$

where A is a constant proportional to Herring's factor, describing the ratio of the optical to acoustical matrix elements $\hbar\omega_0$ is the energy of the optical phonon, ϵ is the energy of the electron. K_0 is the Boltzmann's constant. T is the lattice temperature and $P(\hbar\omega_0-\epsilon)$ is the sticking probability.

$$P(\hbar\omega_0-\epsilon) = 1-\left[1+\left(\frac{\hbar\omega_0-\epsilon}{K_0T}\right)+\frac{1}{2}\left(\frac{\hbar\omega_0-\epsilon}{K_0T}\right)^2\right]\exp.\left(\frac{\epsilon-\hbar\omega_0}{K_0T}\right)$$

2. THE CAPTURE COEFFICIENT

The capture coefficient for an electron of energy $\epsilon\epsilon$ is difined by

$$C(E) = \int d\bar{p}f_0(\epsilon, E)\sigma(\epsilon)v(p)$$

where $f_0(\epsilon, E)$ is the distribution function of electrons and $v(p)$ is the speed of the electron.

The transport equation giving the distribution $f_0(\epsilon, E)$ in the presence of an external electric field when electrons are scattered simultaneously by acoustic phonons and ionised impurities can be written in the dimensionless form

$$\frac{1}{x}\frac{d}{dx}\left[x^2 Y(x)\right] = 0 \qquad \dots (1)$$

where

$$Y(x) = \left\{1+\alpha\frac{x}{(x^2+\lambda)}\right\}\frac{df_0(x, E)}{dx} + f_0(x, E)$$

$$x = \frac{\epsilon}{K_0 T}, \quad \alpha = \frac{E^2}{E_0^2}, \quad E_0 = \frac{4v_s}{\sqrt{3\pi}\mu_L}, \quad E_1 = \sqrt{\frac{32v_s^2}{3\pi\mu_L\mu^*}}$$

$$\mu^* = \sqrt{\frac{\mu_L\mu_i}{6}}, \quad \lambda = 6\frac{\mu_L}{\mu_i}$$

μ_L, μ_i are the mobilities at low fields when electrons are scattered by acoustic phonons and ionised impurities respectively and v_s is the velocity of sound

For fields $E < E_1$ it can be seen that the solution of (1) is

$$f_0(x, E) = A_1\left(\frac{x^2+\alpha x+\lambda}{\lambda}\right)^{\frac{\alpha}{2}}\left[\frac{(\alpha-\beta)x+2\lambda}{(\alpha+\beta)x+2\lambda}\right]^{\frac{\alpha}{2\beta}}\exp.(-x) \qquad \dots (2)$$

where A_1 is the normalisation factor and $B = (\alpha^2-4\lambda)^{\frac{1}{2}}$. For high fields $E > E_1$ the distribution (2) becomes

$$f_0(x, E) = A_2\left(1+\frac{x}{\alpha}\right)^{\alpha}\left[1+\frac{\lambda}{\alpha}\left(\frac{x}{x+\alpha}\right)\right]\exp.(-x) \qquad \dots (3)$$

Here A_2 is another normalisation factor.

The ratio of the capture coefficients with and without fields is therefore :

$$R(E) = \frac{C(E)}{C(O)} = \frac{\int_0^\infty dx f_0(x, E)\sigma(x)v(x)}{\int_0^\infty dx f_M(x)\sigma(x)v(x)} \qquad \dots (4)$$

where $f_M(x)$ is the equilibrium distribution function. At low temperatures $T = 20°K$, $x_{max.} = \frac{\hbar\omega_0}{K_0 T} \gg 1$, therefore, the probability (1) has a maximum at energy $x \leqslant x_{max}$.

For electric fields of interest $E \geqslant 20$ V/cm and $E \leqslant 10^3$V/cm the concentration of electrons with energy $x \approx x_{max}$, is small and the influence of optical phonon emission on the distribution function can be neglected. Therefore, for convenience, the upper limit of the integrals in eq. (4) is approximated to be x_{max}.

Numerical calculations using the IBM-1620 computer have been done for the ratio $R(E)$. The results are shown in figures 1 and 2 for moderate and high fields respectively

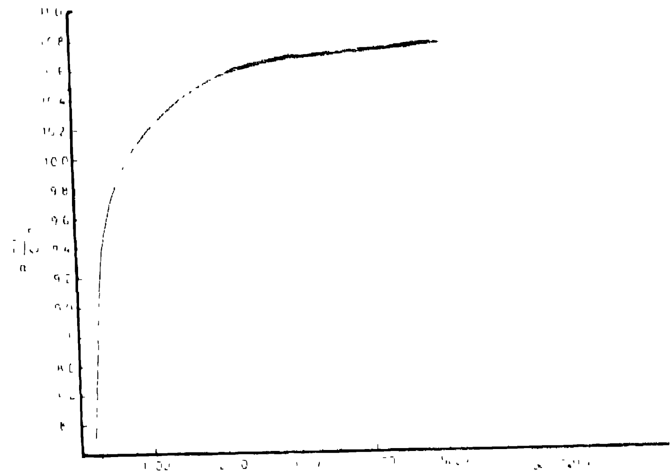

Fig. 1. Variation of ratio of the capture coefficients with the electric field

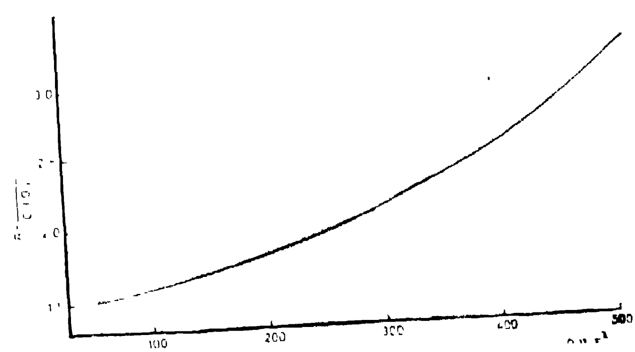

Fig. 2. Variation of ratio of the capture coefficients with the electric field

3. The Electrical Conductivity

The steady stat concentration of hot electrons given from the rate equation Bonch-Bruevich (1964) can be written as

$$n(E) = \frac{n_1}{2}\left[\left(\frac{4N}{n_1}R^{-1}+R^{-2}\right)^{\frac{1}{2}}-R^{-1}\right]$$

For small electron concentrations, i.e. when

$$4NN_0 \gg N_+ n$$

$$n(E) = (n_1 N R^{-1})^{\frac{1}{2}} \qquad \ldots \quad (5)$$

where
$$n_1 = \frac{N_+^{(0)} n_0}{N_0^{(0)}}, \quad N = N_+ + N_0$$

N_+ and N_0 are the concentrations of excited and unexcited donors While $N_+^{(0)}$, $N_0^{(0)}$ are the corresponding thermal equilibrium concentrations

Thus $J = e n_0 \mu_0 \frac{E}{\sqrt{R}}$ and the conductivity σ is given by

$$\frac{dJ}{dE} = \frac{e n_0 \mu_0}{\sqrt{R}}\left[1 - \frac{1}{2}\frac{E}{R}\frac{dR}{dE}\right] \qquad \ldots \quad (6)$$

4. Discussion

The ratio of the capture coefficients in the presence of the electric field and in the absence of it has been calculated. The results show that for small fields this ratio increases slowly. This is attributed to the fact that at low electric fields $x \gg 1$ and the capture probability is small. With the increase of the field the mean energy of electrons is increased and so the capture increases. From eq. (5) it is clear that the stationary state concentration of electrons decreases with the increase of the field. But this decrease in electron concentration is not sufficiently rapid to produce negative differential conductivity.

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